AALTO UNIVERSITY

SCHOOL OF ELECTRICAL ENGINEERING

Department of Radio Science and Engineering

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Pulsed and transient characterization of THz Schottky diodes

The thesis was submitted in partial fulfillment for the degree of Master of Science

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Thesis supervisor:

Professor Antti Räisänen

Thesis instructors:

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SCHOOL OF ELECTRICAL ENGINEERING ABSTRACT OF MASTER'S THESIS

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Any non-linear electronic device can be used for the purpose of frequency mixing or multiplication. But when the frequency is very high (in THz band), only few devices can provide acceptable conversion efficiency and low noise performance. GaAs Schottky barrier diodes are preferred and commonly used in heterodyne receivers as a mixing element. However, at higher frequencies the diode size is small which reduces its thermal capability and the self-heating is significant even for small current levels.

In this master's thesis different electrical and thermal characterization methods for a diode are reviewed. Limitations of the DC I-V measurement method are identified and a test is carried out to study the feasibility of a new pulsed system for characterization of THz Schottky diodes.

The military standard method for thermal impedance testing is studied and suitable modifications to the military standard method are proposed. The transient temperature response of the diode is fitted to an exponential function to extract the junction temperature, thermal impedance and thermal time-constants associated with the internal distribution of thermal resistances and heat capacitances of the diode under test.

Keywords: Schottky diode parameter extraction, pulsed I-V measurement, thermal characterization, self-heating, thermal time-constant, thermal resistance

Preface

This master's thesis has been carried out in the Department of Radio Science and Engineering of School of Electrical Engineering at Aalto University. This thesis is linked to a MilliLab project which has been done in close co-operation with the European Space Agency (ESA) and Technical Research Center of Finland (VTT).

I would like to express my gratitude to my supervisor Prof. Antti Räisänen for giving me the opportunity to work in the field of Radio Engineering. I would also thank him for his guidance, motivation and for creating a good working and research environment at the department.

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I express my sincere gratitude to my family for their blessings, support, love and continuous encouragement in every step of my life. I owe my deepest gratitude to my wife Mrs. Rashmi Dhungel for her love and support. Thank you for always being there for me.

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Espoo, October 3, 2012

Subash Khanal

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Abbreviations

BNC	Bayonet Neill-Concelman
BWO	backward wave oscillator
DUT	device under test
ESA	European Space Agency
GaAs	gallium arsenide
GSG	ground-signal-ground
HEB	hot electron bolometer
LED	light emitting diode
MilliLab	Millimetre Wave Laboratory of Finland
MIL-STD	Military Standard
MMIC	monolithic microwave integrated circuit
PG	pulse generator
RAL	Rutherford Appleton Laboratory
RF	radio frequency
RSU	remote-sense and switch unit
SIS	superconductor-insulator-superconductor
SMA	Sub-miniature version A
SMU	source measurement unit
THz	Terahertz
TSP	temperature sensitive parameter
UMS	United Monolithic Semiconductors
VTT	Technical Research Center of Finland
WGFMU	waveform generator and fast measurement unit

List of symbols

A^{**}	Modified Richardson constant
C_{j0}	Zero-bias junction capacitance
$C_P(T)$	Thermal capacity or specific heat
C_p	Parallel plate capacitance from anode pad to GaAs
C_{pp}	Shunt capacitance due to small fringing field component
E_{00}	Constant with a constant doping density
g	Heat generation per unit volume
I_H	Current applied to the DUT during the heating time
I_M	Measurement current used to forward bias the temperature sensing diode
I_{sat}	Diode saturation current
k	Boltzmann's constant
K	Thermal calibration factor
P_H	The pulse magnitude; product of V_H and I_H.
P_T	Power dissipated in the junction
q	Elementary charge
R_s	Series resistance
r_a	Radius of the anode
S	Diode junction area
T_0	Ambient temperature
T_j	Diode junction temperature
T_{peak}	Peak junction temperature
t_{MD}	Measurement delay time from the start of the heating removal to the start of V_{Ff} measurement
t_{SW}	Sample window time during which the V_{Ff} is measured
V	Applied diode voltage
V_{Fi}	Initial V_F value before application of heating power P_H
V_F	The forward biased junction voltage of the DUT

V_{Fi}	Initial V_F value before application of heating power P_H
V_{Ff}	Final V_F value after application of P_H
V_H	The heating voltage resulting from the application of I_H to the DUT
ρ_θ	Resistivity of the epi-layer material
ρ_m	Material mass density
τ	Thermal time-constant
Φ_B	Schottky barrier height

1 Introduction

1.1 Background, motivation and scope

The terahertz frequency region, spanning from 100 GHz to 10 THz, is considered as an important and useful frequency band for military, scientific, medical and commercial applications [1], [2]. Terahertz remote sensing is used to study the depletion of ozone layer in the atmosphere as the molecules responsible for the ozone depletion resonate in this frequency band [3]. Terahertz radiation can also be used for detection of the concealed weapons [4] in highly secured places for example at the airports. Other application includes radars, data communication, and biomedical imaging which provides numerous opportunities and application possibilities in this frequency region. Also, THz radiation is harmless to the human tissue as it is nonionizing in contrast to the X-rays.

Despite of all these applications and characteristic of THz frequencies, it is the least explored part of the electromagnetic spectrum. The THz frequency region lies in between the microwave and infrared frequency bands. Electronic devices like amplifiers and oscillators are used in the microwave band whereas lasers, LED and optical detectors are common for frequencies above 10 THz [1]. But in between (that is in the THz band) none of these technologies are well fitted. Hence, there appears to be a technological gap in terms of output power and signal detection.

The most applicable field of THz technology these days is in radio astronomy and earth science where the high resolution heterodyne receivers are used to study the different astronomical objects in space as well as in earth's atmosphere, for example star formation regions, molecular clouds, planetary atmosphere, comets and earth's stratosphere [5]. Cryogenic devices such as superconductor-insulator-superconductors (SIS) and hot electron bolometers (HEB) are available at present for THz heterodyne detection. Similarly for THz generation, vacuum tube devices like gyrotons, klystrons and backward wave oscillators (BWO) are in use [6]. These THz detectors and generators are large in size and expensive with limited operational life but for the space exploration missions it is desired that the instruments are small, light, compact and durable. Due to this need, the solid state electronic devices are preferred for THz signal generation and detection.

Any non-linear electronic device can be used for the purpose of frequency mixing or multiplication. But when the frequency is very high (in THz band), only few devices can provide acceptable conversion efficiency and low noise performance. Basically, GaAs Schottky barrier diodes are preferred and commonly used in the heterodyne receiver as a mixing element. The reason behind this preference to the Schottky diode over other semiconductor devices is that it does not have any minority carrier storage (high speed performance). Also GaAs has some features of high mobility, large bandgap and easy processing technology [1], [2] which makes it the best choice for THz receiver element. But as every electronic device has limitation due to the parasitic elements (series resistance and shunt capacitance), increase in frequency will tend to increase the junction capacitance and in order to reduce such capacitance, the diode size should be made smaller.

When the diode size is small, the thermal capability is reduced. Even a current of 1 mA is enough to heat up the submicron anode diodes tens of degrees. Hence, the reduced thermal capability and self-heating of the diode have imposed two challenges. First, the characterization of the diodes using only traditional techniques, such as I-V and C-V measurements, does not provide reliable results as the effect of some diode parameters, e.g., the series resistance is masked by the change of other parameters as a function of the temperature. Second, in many cases thermal constraints have become the limiting factor rather than the obtainable electrical performance. This is especially true when high power varactor diodes are integrated on membrane substrates.

To overcome these limitations, new characterization methods are being developed in this thesis to extract the diode parameters, junction temperature and associated thermal time-constants under known input power level. Measurement based thermal characterization of the THz diodes is still an interesting topic of study as very limited work on thermal analysis of planar Schottky diodes have been carried out.

The scope of this thesis work includes the review of electrical and thermal characterization methods and their limitations. Also the feasibility study is carried out to investigate the suitability of the new pulsed measurement system. The military standard method for thermal impedance testing (MIL-STD 750E) is studied and a modification is proposed. From the results of transient current measurement and temperature controlled I-V measurements, the junction temperature, thermal impedance, thermal resistance and the thermal time-constants associated with the THz Schottky diode are extracted. Measurements are carried out for single anode varactor diodes from two manufacturers (Chalmers University of Technology, Gothenburg, Sweden and Tyndall National Institute, Cork City, Ireland).

2 Schottky diode

Schottky diode consists of a metal-semiconductor junction in contrast to the pn semiconductor junction diode. Commonly a gold or platinum metal contact is established with a semiconductor material such as silicon or gallium arsenide (GaAs). N-type semiconductors are preferred over the p-type since the series resistance is small and has higher cutoff frequency due to larger carrier mobility. Schottky diode is a majority carrier device therefore does not have the recombination time limitation. These diodes are much faster than the pn-junction diodes where the speed is limited by minority carriers [7], [8]. Classification of the Schottky diode can be done into two categories; resistive and varactor diodes. The varactor diodes are used for frequency multiplication purpose whereas resistive (or varistor) diodes serve as mixers, detectors as well as multipliers. Compared to the varistors, varactors have some advantages of high conversion efficiency, power output and breakdown threshold [9].

GaAs based whisker-contact Schottky diodes were in common use over many years in millimeter wave frequency range. Advantages like simple structure, small area device fabrication and reduced junction capacitance made these diodes preferable for the THz receivers. But due to issues of complexity in assembly with integrated circuits and reliability, development toward planar structure diode technology has been in focus. The planar structure diodes enabled the ability for easy assembling and manufacturing of compact and inexpensive receivers [6], [10]. However, due to the planar structure, increase in parasitic shunt capacitance limits the performance of the diodes at higher frequencies. Basically three design parameters of the GaAs Schottky diode, anode diameter, epi-layer doping and epi-layer thickness, can be optimized for its operation in THz frequencies [2]. But the topic of parameter optimization is not within the scope of this thesis.

2.1 Schottky junction and barrier formation

A simple structure of the Schottky diode junction is shown in Figure 1. The junction basically comprises of a n-type semiconductor substrate in contact with the metal. Above the heavily doped n-type substrate, a highly conductive buffer layer is placed which maintains the lower value of series resistance. An epitaxial layer is then grown above the buffer layer which is in contact to the metal forming the Schottky-junction. The doping level of the epitaxial layer is lower than that of the substrate and buffer layer [7].

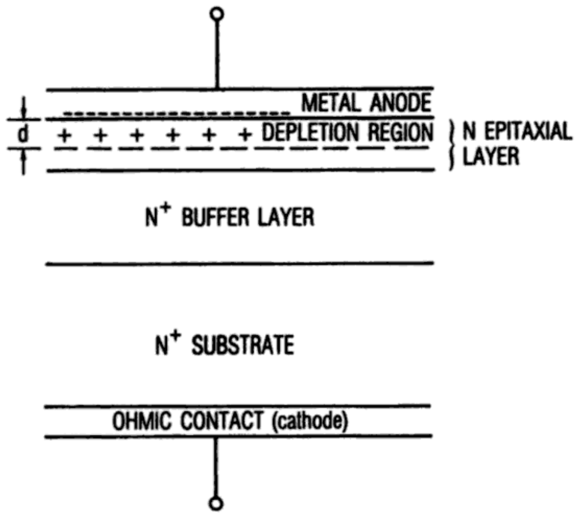


Figure 1: A simple structure of Schottky-barrier diode [7].

Initially the Fermi-energy levels of the metal and the semiconductor are different. But when a contact is established, an equilibrium condition is reached (both materials are in same Fermi-energy level) since the energy in semiconductor is lowered by the flow of some electrons into the metal. The charges accumulated near the contact form a potential barrier known as *Schottky-barrier*. This barrier prevents the electron flow from semiconductor into the metal until any external energy is applied.

When a bias voltage is applied, such that the metal is positive with respect to the semiconductor, the junction is forward biased and current flows through the junction. For opposite polarity, the junction is reverse biased and no conduction takes place. As mentioned earlier, Schottky diodes are majority carrier devices, which mean no minority carriers flow from metal to the semiconductor, hence current stops abruptly if the forward voltage is turned off. This feature of Schottky diode is used for high speed switching in the mixers at high frequencies. Figure 2 presents the energy band diagram of the Schottky-junction [9].

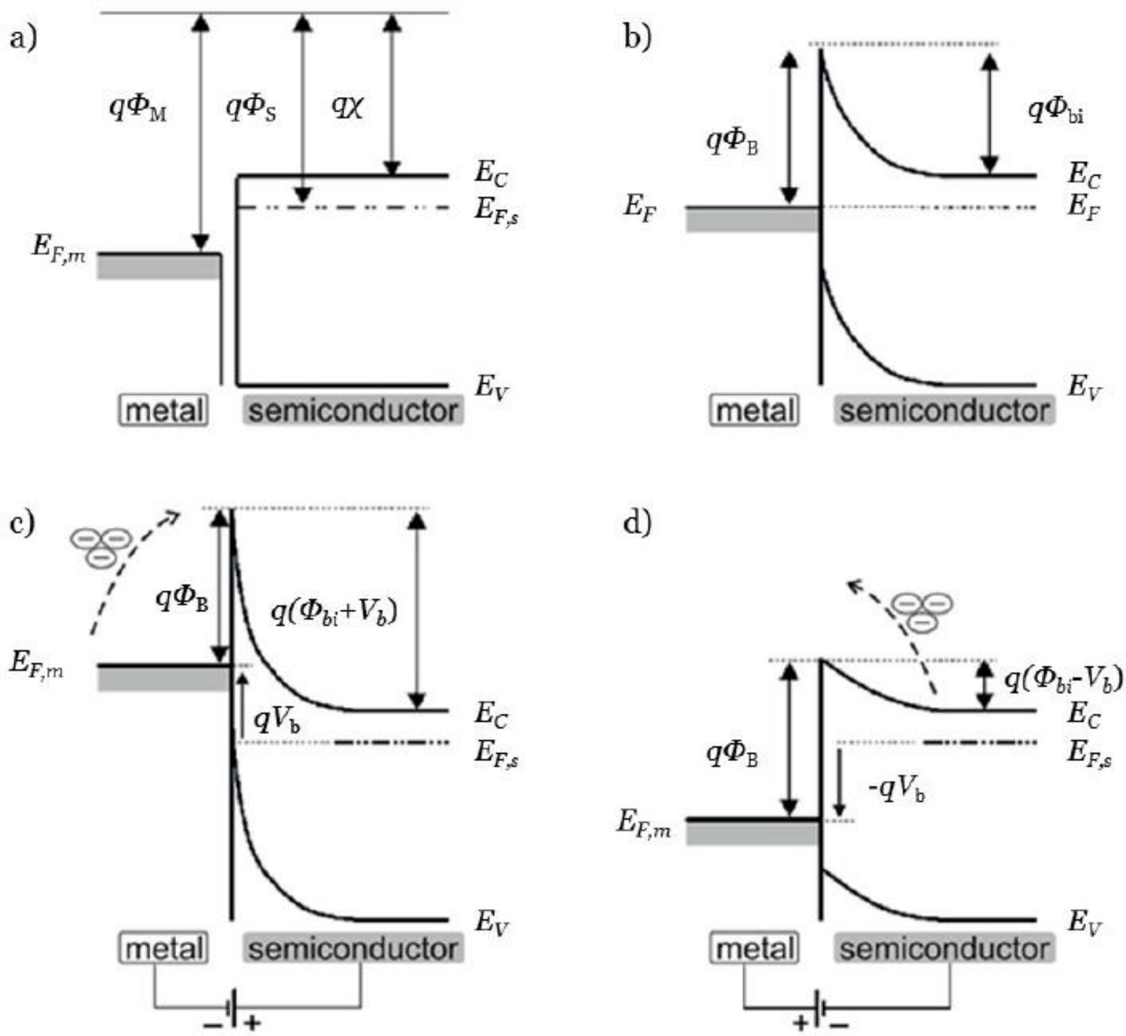


Figure 2: Energy band diagram of the Schottky-junction when a) metal and semiconductor are not in contact, b) two materials are connected forming a Schottky-junction, c) reversed bias Schottky-junction, d) forward bias Schottky-junction [9].

2.2 I-V and C-V characteristics

The current-voltage (I-V) relationship for a Schottky diode can be expressed as in (2.1) [9]

$$I(V) = I_{sat} \exp\left(\frac{q(V - IR_s)}{\eta k T_j}\right), \tag{2.1}$$

where I_{sat} is the saturation current, η is the ideality factor, R_s is the series resistance of the diode, q is the elementary charge, V is the applied voltage, k is Boltzmann’s constant and T_j is the junction temperature. The saturation current can be obtained from (2.2) [9]

$$I_s = SA^{**}T_j^2 exp\left[\frac{-q\Phi_B}{\eta k T_j}\right], \tag{2.2}$$

where S is the junction area, A^{**} is the modified Richardson constant (4.4 $\mathrm{Acm^{-2}K^{-2}}$ for GaAs) and Φ_B is the barrier height.

Schottky diode also exhibits voltage dependent capacitance characteristics due to the charge accumulation near the depletion region which can be presented by equation (2.3) [9]

$$C_j = \frac{C_{j0}}{\left[1 - \frac{V}{\Phi_B}\right]^{1/2}}, \tag{2.3}$$

where C_{j0} is the zero-bias junction capacitance. The capacitance of a Schottky diode depends on factors like doping profile of semiconductor and size of the junction. Also the width of the depletion region is narrower when the diode is forward biased and wider during reverse biased condition.

2.3 Effect of temperature in diode characteristics

Effect of external environment temperature variation can be observed in the I-V characteristics of Schottky diode as a shift in the knee voltage [8]. As the temperature rises, the knee moves towards the lower voltage and vice versa which means at a constant voltage, current is larger for higher temperature. This effect can be observed in Figure 3 where the I-V curves of a test diode are plotted for different temperature points.

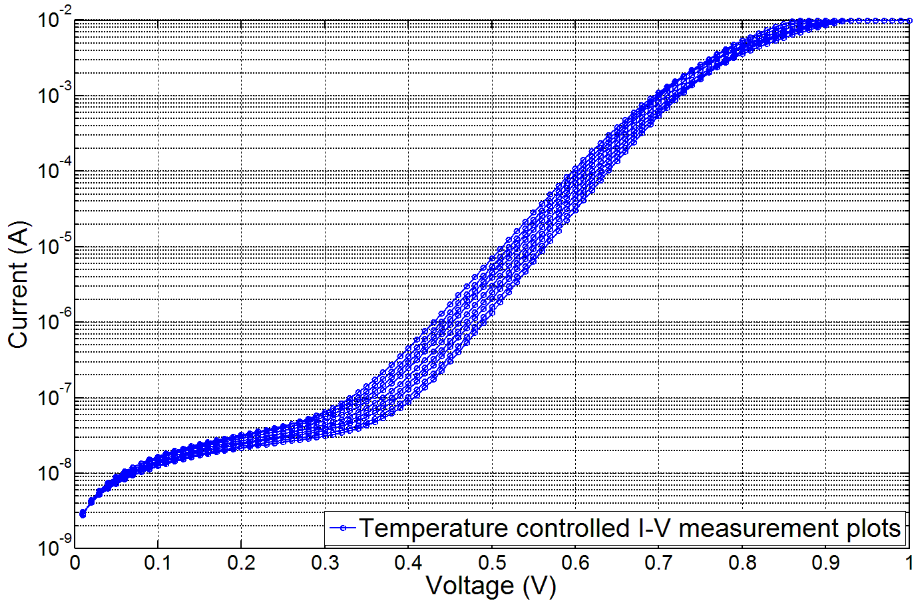


Figure 3: Temperature dependent I-V curves for a test diode. Temperature range from 300 K to 340 K. Y-axis is in semi-logarithmic scale.

Effect of temperature on C-V characteristics can be viewed as a relation to the bias voltage. Rise in temperature shifts the knee to lower voltage as explained earlier. Hence, the diode now needs to be biased at lower voltage, resulting in reduced junction capacitance (2.3).

2.4 Planar Schottky diode equivalent circuit

The basic equivalent circuit for planar Schottky diode is presented in Figure 4 [11]. Here the junction resistance and junction capacitance are denoted by R_j and C_j, respectively. The resultant resistance caused by the substrate and the undepleted epitaxial layer is represented by series resistance R_s and C_p represents the parasitic parallel capacitance.

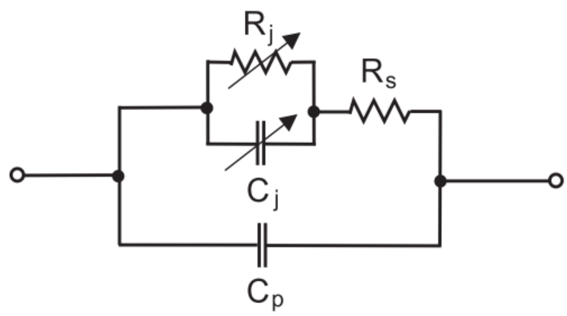


Figure 4: Planar Schottky diode equivalent circuit [11].

2.5 Schottky diodes for high frequency applications

The use of planar Schottky diode technology for THz applications provides the ability to build compact and inexpensive receivers. Also the integration with other circuitry has become simple. But the parasitic effect at higher frequencies limits their operation. Hence, it is desirable to build low-parasitic capacitance diodes that are easy to fabricate. A low parasitic whiskerless diode structure is presented in [10]. Figure 5 presents such surface channel planar Schottky diode which has lower junction and shunt capacitances. By the term ''*Surface channel*'' means a narrow air gap made in the GaAs and semi-insulating substrate (between anode contact pad and the cathode) which terminates the current flow from C_p to anode. Resulting capacitance arises only from C_{pp} in the semi-insulating GaAs which is very small. Hence this diode structure has low parasitic capacitance [8], [10].

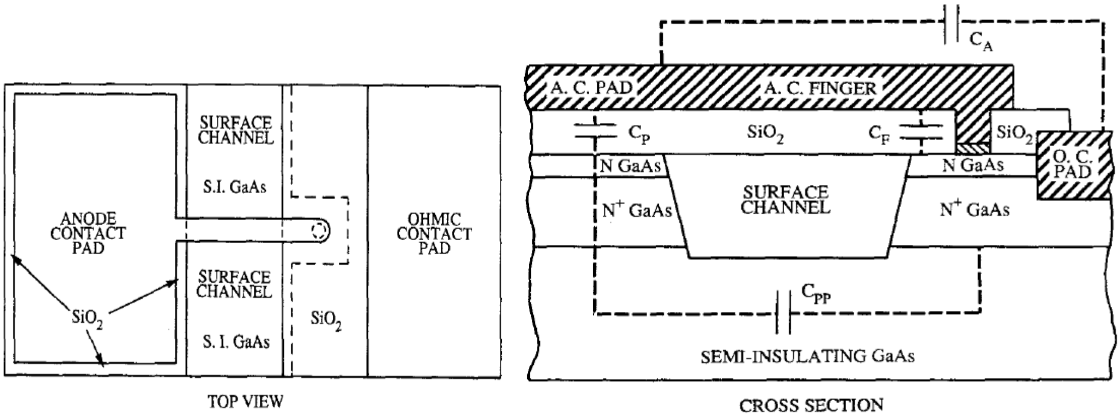


Figure 5: Top and cross-sectional view of a surface channel Schottky diode [10].

In general, Schottky diodes are used in frequency mixing and power detection at higher frequencies. GaAs based Schottky diodes can provide reasonable conversion efficiency for frequency mixing. High speed switching capability of these diodes has made them the device of choice in THz frequencies. The Schottky diode is a vital element (as mixer) in the THz heterodyne receivers.

An important design variable of the Schottky diode is the ''*Barrier Height''*. In comparison to the pn-junction diode, the Schottky diode can have lower forward voltage for a specific current level. It behaves as an ideal rectifier whose forward voltage can be selected. This provides the diode an ability to operate as a detector device for a very week signal.

2.6 Schottky diodes used in this task

Single-anode varactor Schottky diodes from two different manufactures (Chalmers University of Technology, Gothenburg, Sweden and Tyndall National Institute, Cork, Ireland) are used for electrical and thermal characterization in this thesis work. At least two samples from each manufacturer are mounted over an on-wafer co-planar waveguide (CPW) quartz carriers and the measurement is performed using a semiconductor parameter analyzer and probe station. Figure 6 presents the pictures of two single-anode varactor diodes and their carrier structures.

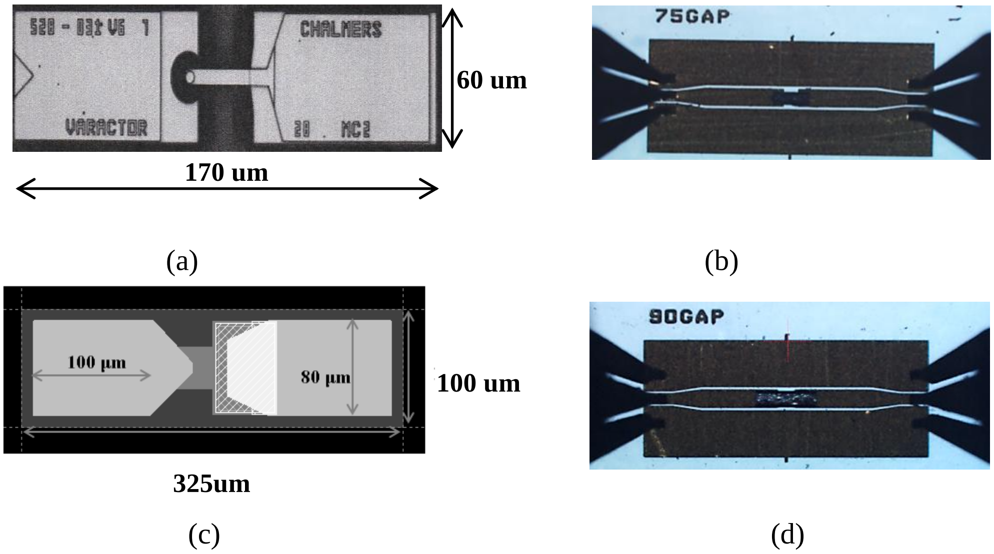


Figure 6: Photographs of (a) Chalmers single-anode varactor diode structure; (b) Chalmers diode on quartz carrier with probes in contact; (c) Tyndall single-anode varactor diode ; (d) Tyndall diode on quartz carrier.

Table 1 lists the electrical parameters namely the series resistance (R_s), ideality factor extracted from DC I-V measurements and the dimensions of the diodes used in this work.

Table 1: Schottky diode parameters (extracted) and dimensions.

Diode	R_s (Ω)	η	Length (µm)	Width (µm)	Anode area (µm^2)
Chalmers Varactor A6	3.1	1.18	170	60	9
Chalmers Varactor A10	4.5	1.16	170	60	9
Tyndall Varactor 4u	8.6	1.14	325	100	38
Tyndall Varactor 5q	7.1	1.12	325	100	38

2.7 Electrical parameter extraction methods

The most commonly used electrical characterization technique for Schottky diodes is the DC I-V parameter extraction where the parameters (I-V characteristics, ideality factor, saturation current, and series resistance) are extracted from the diode current-voltage measurements. Two approaches can be followed to extract the diode parameters. Fist a two-step method can be used where ideality factor and the saturation current are extracted from the linear part of the current-voltage characteristics and then the series resistance is extracted in next step [11]. In second approach, the parameters are obtained by fitting the diode equation (2.1) with the measurement data using least squares error method [9].

This traditional DC measurement method is based on the assumption that the temperature of the diode, the ideality factor and saturation current remain constant throughout the measurement session. But in reality, the bias current increases the temperature of the diode junction (2.4) which in turn leads to different values of ideality factor and saturation current at different measured I-V points as from (2.5) and (2.6) [12]

$$T_j = T_0 + P_T R_\theta \,, \tag{2.4}$$

where T_0 is the ambient temperature, P_T is the power dissipated in the junction, and R_θ is the thermal resistance of the diode.

$$I_s = SA^{**}T_j^2 exp\left[\frac{-q\Phi_B}{\eta k T_j}\right], \tag{2.5}$$

$$\eta = \frac{q}{kT_j} E_{00} coth\left[\frac{qE_{00}}{kT_j}\right], \tag{2.6}$$

where S is the junction area, A^{**} is the modified Richardson constant, Φ_B is the barrier height and E_{00} is a constant with a constant doping density.

2.8 Limitations of prevailing methods for diode parameter extraction

Temperature dependence of the saturation current and ideality factor of the Schottky diode has significant effect when the parameter extraction methods are used for diodes that are optimized to work in high millimeter wave and THz frequencies. At higher frequencies, the anode junction size becomes smaller and the thermal capability of the diode is reduced. The prevailing inaccuracy in the DC I-V measurement results is due to two factors, self-heating of the device and the trapping effects [14]. Static DC I-V measurements performed at different bias conditions can provide good results if the thermal effects and trapping effects are negligible. But for the cases where the thermal and trapping effects can change with the DC bias, the errors in the obtained result is significant [14]. In this thesis work only the self-heating of the diode is studied and the trapping effect is left out for future work.

To overcome these limitations, new characterization methods are being developed to accurately estimate the diode parameters and junction temperature under known input power level. I-V measurements should be performed with a fast signal such that the rise time of the signal is less than the thermal time constant of the diode.

2.9 Pulsed I-V and transient measurements of THz Schottky diodes

Pulsed I-V measurement provides the capability to make an isothermal measurement for such devices where the self-heating can affect their I-V characteristics. Electrical parameter extraction using pulsed measurements can be fast enough such that the diode under test has no time to react thermally. Hence, a measurement system that provides simultaneous source-and-measure capability for pulse lengths in the order of hundreds of nanoseconds is essential for accurate measurement of the pulsed response and the extraction of diode electrical parameters.

Transient measurement is associated with the thermal characterization of Schottky diodes where the heating pulse is applied for certain time duration and is abruptly stopped letting the diode to cool down. The current response of the diode for total heating and cooling sessions are measured. The current response is then converted into the temperature response with the help of current-temperature calibration obtained from the temperature controlled I-V measurements. The transient measurement procedure and results are explained in detail later in the thesis.

2.9.1 Semiconductor parameter analyzer for pulsed and transient measurements

Pulsed and transient measurements are conventionally performed using a setup of a pulse or a function generator, an I/V converter and an oscilloscope. In such setup, measurement errors can arise from the complicated cabling between the instruments and also due to the errors contributed by each individual component. Also it is very challenging to build a synchronized source-and-measurement system capable to isolate the effect of input pulse in the measurement output. Therefore, it is desirable to have a measurement system that can generate short pulses in one channel and measure the current response on the other without the need of complex cabling. In this task, Agilent B1500A Semiconductor Parameter Analyzer is used which can produce short pulses in the order of hundreds of nanoseconds and measure current in a separate channel.

The semiconductor parameter analyzer includes a Waveform Generator/Fast Measurement Unit (WGFMU) module which is capable of performing dual functionality. First, arbitrary linear waveform generation with 10 ns time resolution and second, high speed/high resolution current/voltage measurement with 200 mega-sample/second sampling rate and 2 nA current resolution. The WGFMU module supports the output voltage ranges of: ±3V, ±5V, -10 V to 0 V and 0 V to +10 V. The resolution of the output voltage is 96 μV for the ± 3 V range and 160 μV for the other ranges [15].

Calibration is performed using built in ‘‘Module Self Calibration’’ feature of the parameter analyzer. The probes are lifted up and the selected modules are calibrated which represents the open standard calibration procedure.

WGFMU can be used in two operation modes: PG (Pulse Generator) mode and Fast I-V modes. In fast I-V mode five fixed current measurement ranges (from 1 μA to 10 mA) are available. The measurement resolution is 0.014% of range and the noise floor is 0.2% of range [15]. WGFMU can perform measurement in synchronization with the applied waveform, which enables accurate high-speed I-V characterization. In addition, some other features include hardware averaging for noise reduction, and multiple sampling rates within the single waveform. Hence due to the combination of fast and precise current measurement capability, arbitrary waveform generation and other features of the WGFMU, this system is suitable to our measurement requirements for the pulse and transient characterization of the THz Schottky diodes.

Figure 7 presents the schematic diagram for the configuration of pulse/transient measurement system using WGFMU. Each WGFMU module is connected to the Remote–sense and Switch Unit (RSU) where the current/voltage measurement is carried out. The force voltage is supplied from the WGFMU and the current (or voltage) measurement is performed in RSU according to the mode of operation. Figure 8 shows the internal circuit diagram of the WGFMU module and RSU and their operation in different modes. RSU is placed near to the DUT for fast and accurate measurements and simple cabling setup. The outputs from the RSU are then fed to the RF probes using SMA (male) cables. The probes used here are the Cascade Ground-Signal-Ground (GSG) probes.

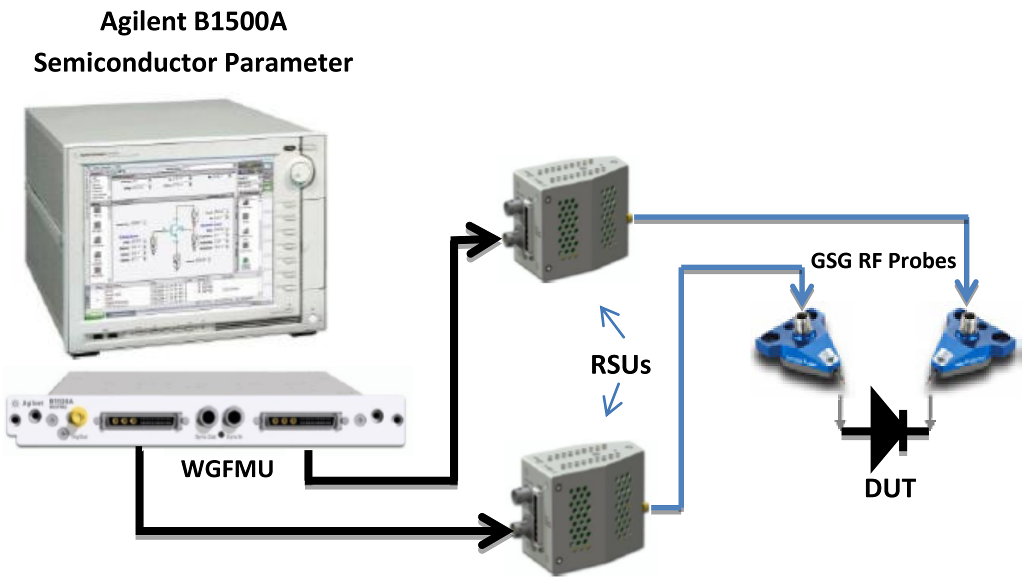


Figure 7: Configuration of pulse/transient measurement system using the WGFMU.

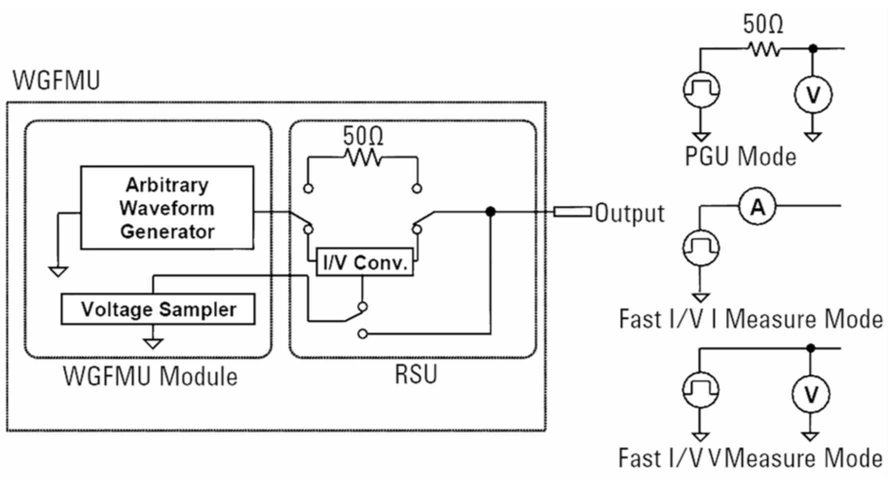


Figure 8: Circuit diagram for WGFMU and its operation modes [15].

3 Thermal characterization of THz Schottky diodes

Thermal characterization of a semiconductor device refers to the measure of the temperature response due to the internal self-heating [16]. The semiconductor diode junction heats up as current flows during the device operation. The heat generation is large and concentrated in a small region. This heat diffuses out to the package (chip-solder-case) and then eventually to the local ambient according to the laws of thermodynamics and heat transfer. Also as the operation frequency increases, the size of the semiconductor diode is reduced to avoid the parasitic effects. But with the reduced size, the thermal capability (ability to remove the heat away from the junction) is degraded. The performance and the reliability of the semiconductor devices depend on their operating temperature [17]. Hence, thermal characterization of the diodes is essential to accurately estimate the junction temperature as function of time and associated thermal time-constants (chip-solder-case) for thermal modeling of the device self-heating.

3.1 Steady state and transient thermal states

When a semiconductor device is constantly powered for a long period of time, it undergoes transition from the initial unpowered thermal equilibrium condition to a new steady state equilibrium condition. The state before the device reaches the equilibrium is known as transient thermal state. In this transient process, the temperature is varying and tends toward thermal equilibrium. The transient behavior of the device is due to the presence of thermal mass or heat capacitance that should be charged as the thermal equilibrium condition changes. In order to determine the thermal resistance these heat capacitances between the isothermal surfaces should reach the thermal equilibrium condition, which means the temperature is not changing anymore due to charging of the heat capacitances [16].

3.2 Thermal resistance and thermal impedance

Thermal resistance of a semiconductor device is defined as a ratio of the temperature difference between two imaginary isothermal surfaces to the total heat flow between them [16]. Alternatively, thermal resistance is also defined as the junction temperature rise above the reference temperature divided by total electrical power dissipated in the device. If T_j is the temperature of the junction (hot surface) and T_0 is that of the surrounding (cold surface), and P_T is the total power dissipated in the device (total heat flow rate) then the thermal resistance is written as

$$R_\theta = \frac{T_j - T_0}{P_T}. \tag{3.1}$$

Thermal resistance of a semiconductor diode is the measure of ability to remove the heat generated in the junction. It is an important parameter for characterization of small anode area Schottky diodes since its effect is significant in the current-voltage characteristics.

Thermal impedance is defined at the transient state of the device. At thermal equilibrium, the thermal impedance is equal to the thermal resistance. In order to determine the thermal impedance, information of the powering condition and time duration is essential which is not required for thermal resistance. By definition, thermal impedance is the difference in temperature between two isothermal surfaces divided by the heat flow entering the hotter of the two surfaces

$$Z_\theta(t) = \frac{T_j(\mathrm{t}) - T_0}{P_T} . \tag{3.2}$$

3.3 Thermal characterization methods for diodes

Different methods for thermal characterization of a semiconductor device are available. Pulsed measurements, imaging methods and electrical junction temperature measurements are some commonly used methods for extraction of junction temperature and thermal resistance which are discussed below. Using the information of the ambient temperature and the power dissipation, the thermal resistance is calculated once the junction temperature is extracted.

3.3.1 Transmission line pulse (TLP) method

Based on the transient electrical stress of the device, this method is used for the excitation of the degradation and ageing mechanisms [18]. Thermal time constant is used to characterize the thermal properties of a device and is a measure of time response of the device after thermal excitation. Different thermal time-constants, for example *Intrinsic time-constant* (for device junction) and *Peripheral time-constant* (for contact metallization, substrate), can be calculated. For the pulse length less than the peripheral time-constant, the thermal power is dissipated only in the junction and the temperature can be deduced. To calculate the thermal time-constants, pulsed signal is applied to the diode and the voltage response is monitored. By fitting this pulse response to an analytic exponential function, the time constant is extracted. From the time constant one can estimate the temperature of the diode junction during pulsed stress. Disadvantage of this method [18] is that the application of the pulsed signal and the voltage response measurement are made at the same node in the measurement setup. This makes it challenging to separate the voltage response from the input signal.

3.3.2 Infrared (IR) imaging method and liquid crystal imaging

Determining the temperature of the chip and the thermal resistance from IR imaging is straightforward. The temperature is measured using an IR microscope and the thermal resistance is calculated with (3.1). Disadvantage of this method is that the structures that are covered with opaque material cannot be measured. Also the spot size of current state-of-the-art IR microscopes is ~ 3-5 µm, making the measurement of very small structures uncertain.

Liquid crystal is used in the imaging method to evaluate the temperature of the device. Liquid crystal responds to the temperature variations and this response is used to measure the part of the device that is coated with liquid crystal. Liquid crystal has a unique property of reflecting the visible light of different wavelengths for different temperatures [19]. This property of the crystal is utilized in the imaging method. As the temperature changes different wavelengths of visible light start to reflect and the temperature variation can be observed from this phenomenon [20]. The junction of the diode has to be exposed if the junction temperature has to be known. Though this method can give a good spatial response and temperature map can be generated, it is quite expensive and only applicable to diodes whose junction is visible.

3.3.3 Electrical junction temperature measurements

The electrical method for junction temperature measurement is a commonly used, direct and non-contacting technique for evaluating the thermal performance of semiconductor devices which uses the junction as the temperature sensor. The method uses the electrical-temperature properties to measure the temperature of the semiconductor junction. In practice, the forward voltage drop in the junction is used as the temperature sensitive parameter (TSP). Voltage-temperature relationship for semiconductor devices is characterized generally by a nearly linear relationship between the forward voltage drop and junction temperature when a constant current is applied to the device. This constant current is known as the measurement or sense current and need to be small enough not to cause significant self-heating. The calibration equation for V-T relationship is expressed as [16]

$$T_j = m * V_F + T_0 \,, \tag{3.3}$$

where ‘m’ is the slope, T_0 is the temperature intercept and V_F is the temperature sensitive parameter. Here slope and intercept are the calibration parameters and are specific to the DUT. Hence calibration is required to be performed for each distinct DUT. After calibration, the junction can be used as the temperature sensor which is able to measure the temperature using the forward voltage measurement obtained from the application of the sense current (3.3).

3.3.4 S-parameter and temperature controlled I-V measurements method

In this method, thermal resistance is extracted based on the combination of the I-V measurements at different controlled temperatures and on the S-parameter measurement results at a known ambient temperature [9]. The theoretical models are verified with the measurement results for temperature dependent saturation current and ideality factor. The S-parameter measurements are carried out in the low frequency and high bias current region. This method takes into account the effect of the self-heating of the anode junction on the extracted values of series and thermal resistances. This method is laborious as it needs several sets of I-V measurements and S-parameter measurements for diode parameter extraction.

3.4 Comparison between the thermal characterization methods

Different thermal characterization methods discussed earlier in the text have their own advantages as well as disadvantages. It is challenging to make conclusions on the accuracy and suitability of one method over another as one method can be best suited in the particular measurement situation and the DUT which may not be feasible for other. For example, imaging method using liquid crystal is most suitable in the case of chip level temperature measurement where this method can produce accurate results with high spatial resolution. But the disadvantage of this method is that it can only be implemented and limited to the junctions that are directly visible where the liquid crystal can be applied. Also this method is quite expensive.

Electrical method is a direct and non-contacting technique that can be performed without any sensor using only the electrical-temperature properties of the semiconductor junction. The forward voltage drop can be used to estimate the temperature of the junction. Here only one average temperature is measured rather than the temperature distribution and due to this reason the temperature map cannot be generated as compared to the imaging method.

The electrical method also has to deal with the self-heating effect during calibration procedure [16], [17]. TSP is calibrated usually by adjusting the temperature of the device to known temperature points and then measuring the electrical parameter at each point. Assumption is made that the device is at the same temperature as the environment (oven, bath or hot plate) and there is no self-heating. This may not be true as some heat is dissipated when the device is active which may result in higher extracted temperature. This effect of self-heating can be minimized if the power dissipation is kept very low during calibration which can be achieved if the measurement (or sense) current level is selected carefully.

Usually in the electrical method, a known power level is applied to the DUT and then switched off to very low value for very short time period during which the temperature sensitive parameter is measured. This TSP is compared with its initial value from the calibration performed at various temperatures. However the problem still persists due to the transient electrical signals (during switching from high power to lower value) that interfere with the measurement. Some delay is introduced for the electrical signal to settle down to the calibration level. And during this delay the device cools down. This problem can be addressed if the measurement is performed such that the switching between the heating and measurement is fast enough and the TSP measurement is carried out as soon as the heating signal is interrupted so that the device does not cools down significantly.

MIL-STD 750E, method 3101.4, the thermal impedance testing for diode is discussed in the section 3.5 in detail which is similar to the electrical method. Forward diode voltage is used as the temperature sensitive parameter. In section 3.6 a modification to the MIL-STD method is proposed where the diode current is used as the temperature sensitive parameter. The modified method is suitable for the measurement of small THz diodes for several reasons. First the current measurement is done on a separate channel than the applied voltage pulse. Thus the interference due to the reflected pulse is minimized. Second, diode cooling (full ‘‘cooling curve’’) is measured and extraction of the junction temperature and thermal time-constants is performed using least-square errors fitting of the results to an exponential function (as in [18]).

3.5 MIL-STD-750E method 3101.4: Thermal impedance testing of diodes

Determination of the thermal response of the semiconductor device can be performed by using two approaches, steady-state thermal impedance or transient thermal impedance testing. The overall thermal performance of the device is based on the thermal impedance testing where as a transient test, a part of thermal impedance test, provides the measure of the thermal quality of the die attachment. The method is applicable to the rectifier diodes, transient voltage suppressors, power zener diodes, and some zener, signal, and switching diodes.

For a small area junction diode, that cool rapidly, a current is applied in forward direction and measurement is performed close to the heating current termination. The thermal time constant of the chip is shorter than that of the package. Hence the transient measurement can be performed by selecting the width of heating pulse such that only chip and chip-to-substrate interface are heated during the pulse. This can be obtained if the pulse width is a bit larger than the thermal time constant of the chip and less than that of the substrate [21].

3.5.1 Test setup

Figure 9 present the thermal impedance test setup for the diodes. The setup consists of a constant current source to supply the heating current (I_H), a constant current source for measurement current (I_M) sufficient enough to turn on the junction of the diode, an electronic switch with the ability to perform switching between the heating period and measurement and a voltage measurement circuit accurate enough to make the measurement with millivolt resolution. The switching process should be very fast to avoid DUT cooling during the transition.

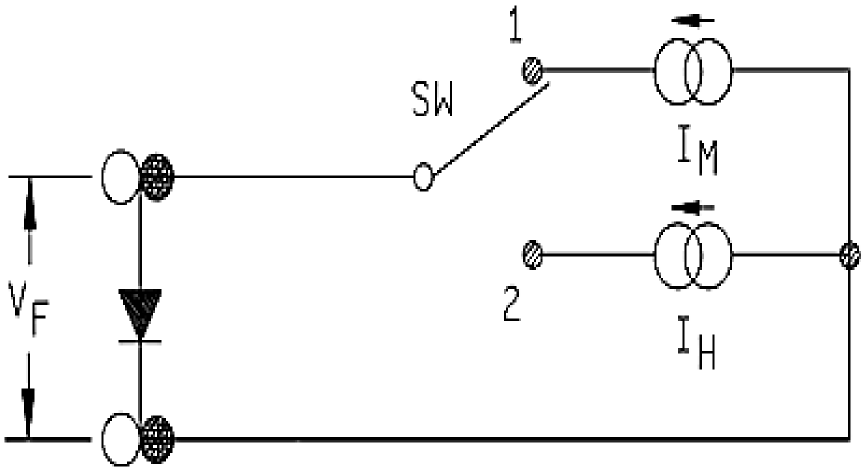


Figure 9: Thermal impedance testing setup for diodes as illustrated in MIL-STD-750E Method 3101.4 (according to [21]).

At first the I_M and I_H current sources are set to desired values. When the switch is in ‘‘Position 1’’, no heating pulse (P_H) is applied. Here the value of the initial forward bias voltage (V_{Fi}) is measured. Now the switch is moved to ‘‘Position 2’’ for the time t_H (duration of P_H applied to the DUT) and the heating voltage (V_H) resulting from the application of I_H is measured. At last the switch is moved again back to ‘‘Position 1’’ and the final value of the forward bias voltage (V_{Ff}) is measured within the time interval of t_{MD} + t_{SW}. Here t_{MD} is the measurement delay time from the start of the heating removal to the start of V_{Ff} measurement and t_{SW} is the sample window time during which the V_{Ff} is measured. The change in the forward voltage ΔV_F (difference between V_{Ff} and V_{Fi}) is calculated. The current sources are then turned off at the end of the test. The timing waveform diagram in Figure 10 illustrates the test steps graphically.

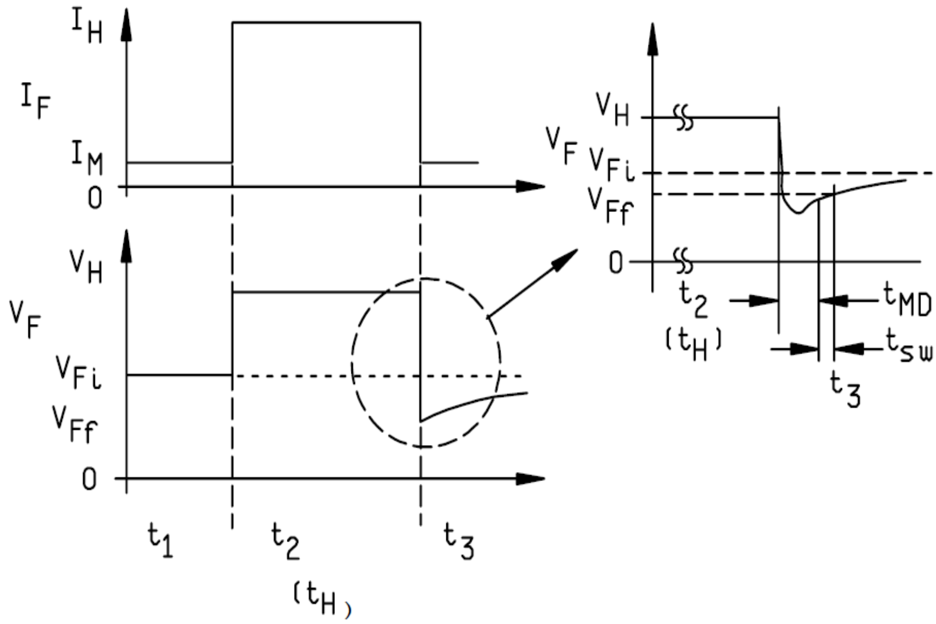


Figure 10: Thermal impedance testing waveforms for forward bias method [21].

3.5.2 Measurement of temperature sensitive parameter V_F

In this method, the temperature sensitive parameter is the forward diode voltage V_F. For this reason it is also called ‘‘forward bias method’’. Calibration of junction temperature versus V_F is performed by monitoring the the forward voltage for the desired measurement current as the temperature is varied. The choice of I_M is to be made such that V_F is decreasing linearly over the junction temperature range. Also the measurement current should be large enough to turn the diode junction on but small enough so that the self-heating is not significant. The V_F versus temperature relationship is first determined by driving the diode with the measurement current and adjusting temperature. The resulting points are graphed and the relationship is reduced to a single slope calibration factor called the K-factor (Figure. 11) defined as

$$K = \left|\frac{T_{j2} - T_{j1}}{V_{F2} - V_{F1}}\right|, \qquad (3.4)$$

where V_{F2} and V_{F1} are the forward diode voltages at temperatures T_{j2} and T_{j1}.

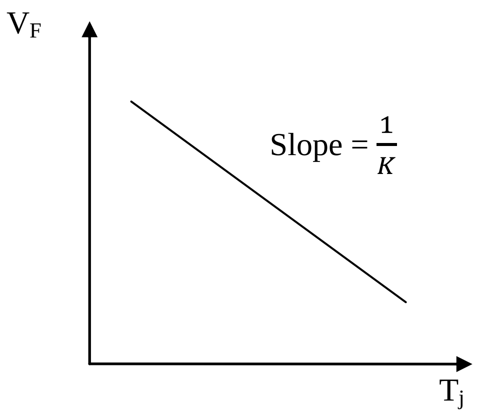


Figure 11: Example calibration curve of V_F versus T_j.

In summary, the diode is driven with the high heating current for a fixed period of time. The heating signal is terminated abruptly and switching to the low measurement current is performed. This switching to lower measurement current is essential as the calibration data is valid only at this current levels and the conversion from voltage to temperature values is possible. Forward voltage (V_F) is then measured as soon as possible after the termination of the heating current so that the diode does not cool down. The wait time depends on the transient settling time of the measurement system. Now the measured V_F is then compared with a V_F measurement taken before applying the heating signal. Once the calibration factor (K) and the forward voltage change (ΔV_F) are known, junction temperature and thermal impedance of the diode can be calculated from equations (3.5), (3.6) and (3.7)

$$\Delta T_j = K\Delta V_F \, , \qquad (3.5)$$

$$T_j = T_0 + \Delta T_j \,, \tag{3.6}$$

$$Z_\theta = \frac{\Delta \mathrm{T_j}}{P_T} = \frac{K \Delta V_F}{I_H V_H} \qquad [K/W]. \tag{3.7}$$

From the knowledge of the thermal impedance for different heating durations, a complete thermal response of the diode ranging from transient to steady state can be determined. The process of determining the thermal response of a semiconductor device to a step-heating situation is known as ‘‘heating characterization’’ and the curve that shows the relation between the thermal impedance of the device to the applied heating time is known as ‘‘transient response’’ or ‘‘heating curve’’ [22]. These curves are able to reveal the distribution of thermal resistances and capacitances within the device.

3.6 Proposed modification to MIL-STD method for transient measurement of Schottky diodes

This method is a proposed technique for thermal characterization of the THz Schottky diodes which is similar to the MIL-STD method discussed above. The difference is that in this method, forward diode current is used as the temperature sensitive parameter rather than the forward bias voltage as in [21]. The procedure is similar to the one explained in section 3.5 but the voltage pulse is used instead of the current pulse to heat up the diode.

The reason behind the choice of the diode current as the temperature sensitive parameter is that the used measurement system can not provide fast current sourcing capability. Hence, short voltage pulses are applied for desired heating time using WGFMU in Fast IV mode with an accuracy of $\pm$0.1 % of the value entered [15]. The heating voltage is abruptly changed to measurement voltage and the current measurement is performed. The transient characterization procedure for THz Schottky diodes can be explained with following steps:

Step 1: DC current-voltage characteristics of each diode under test are measured initially.

Step 2: The selection of heating current and the measurement current (I_H and I_M) is performed. The heating current is normally selected in the range of a few mA. The selection of measurement current is made such that it is low enough not causing significant self-heating but large enough to turn the diode on. For the test case in this thesis, the heating current level is chosen to be 8 mA and the measurement current level as 100 μA.

Step 3: After the selection of heating and measurement current levels, the corresponding voltages (V_H and V_M) are acquired from the DC I-V curves for each diode measured in step 1. These voltages are applied to the diode during heating and measurement durations respectively.

Step 4: The heating duration might range from some microseconds to seconds depending on the device under test. After the heating pulse, the voltage level is changed to measurement voltage and the corresponding transient current response is measured.

Too short a heating voltage pulse will not heat up the area farther away from the junction. Hence, to extract all the thermal time-constants and thermal resistances from the transient response, the heating voltage pulse is applied until the thermal equilibrium is reached. This may take up to couple of seconds.

Step 5: The extraction of junction temperature from the transient current response requires current-temperature calibration which is obtained from the temperature controlled I-V measurements. For each diode, the I-V characteristic is measured at controlled temperature points. From these I-V plots, the current levels at the controlled temperature points are extracted at a constant voltage (measurement voltage V_M). These current levels are then used to establish the relationship between the temperature and the diode current.

Step 6: Finally, the thermal time-constants and the temperatures corresponding to the intermediate equilibrium stages (4.1) are extracted from least squares curve fitting of the cooling curve. From the same curve fitting, the peak junction temperature is extrapolated. With these information of the junction temperature, power dissipation, thermal time-constants and the ambient temperature, the thermal resistances and heat capacitances are computed.

Each step listed above is explained in detail in Chapter 4 *Schottky diode measurements*. The hardware setup for the transient thermal testing is as shown in Figure 7. As in the setup, voltage sourcing and current measurement are performed in two different channels (ports) such that the input is isolated from the current measurement. The measurement setup can be prepared using the EasyExpert software available in the Agilent semiconductor parameter analyzer. In this method, the diode is subjected to the heating voltage for different time periods.

Figures 12 and 13 present an example of the diode heating pulse and current sampling measurement sequence diagram (respectively) used in the modified MIL-STD method.

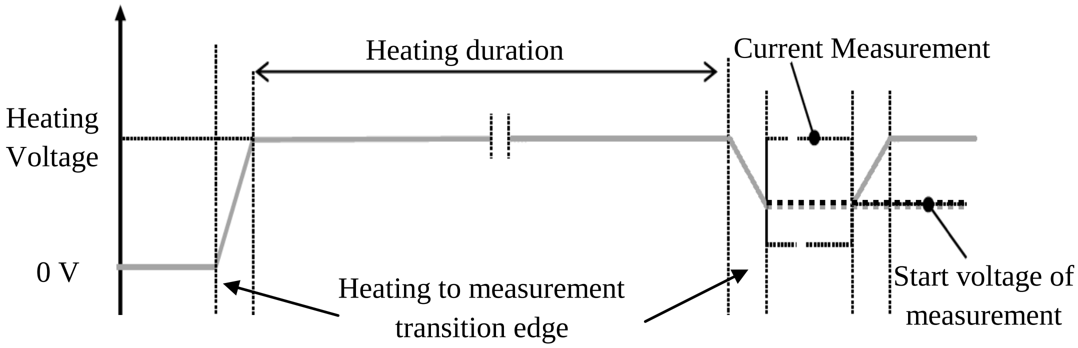


Figure. 12: Example diode heating and current sampling measurement pulse diagram.

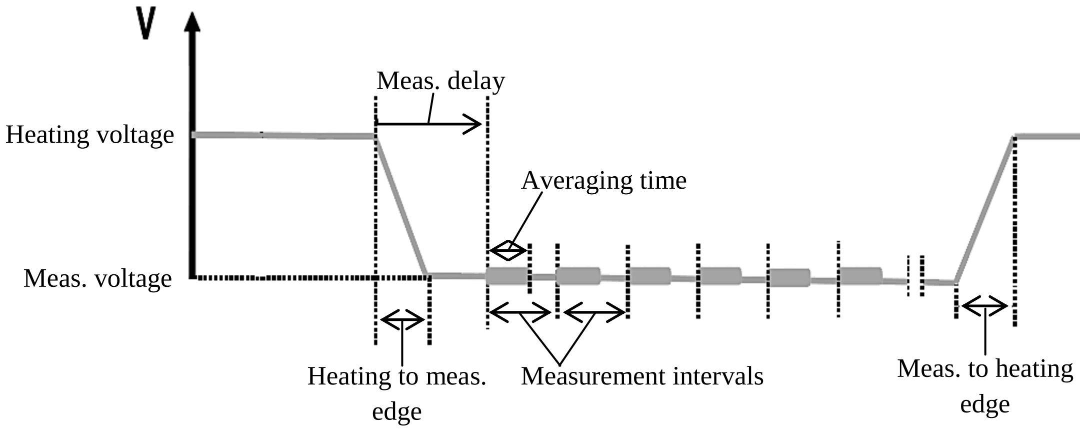


Figure 13: Measurement sequence diagram for current sampling.

The corresponding software setup example for the diode measurement is presented in Figure 14. The maximum current range available in the instrument is 10 mA. The duration of the heat applied to the diode can be defined in the *Accumulated_Stress_Time* box where the heating times are stored in the form of vectors. The *VgStress* and *VgMeas* are the heating and measurement voltages corresponding to the heating current (8 mA) and measurement current (100 uA). A suitable measurement delay can be set using *MeasDelay* input box. For example, if the measurment delay is set to -1 μs, then the parameter analyzer start the current measurement 1 μs before the heating voltage steps to the measurement voltage. The current can be sampled with the resolution of 10 ns (minimum) and the measurement time can be set by changing the number of points. Here *SeqDelay* is the device delay time and averaging time for one measurement is defined in *IntegTime*. The voltage change time between the heating and the measurement voltage is defined in *TransEdge* whereas wait time at this transition is defined in *RangeChangeHold*.

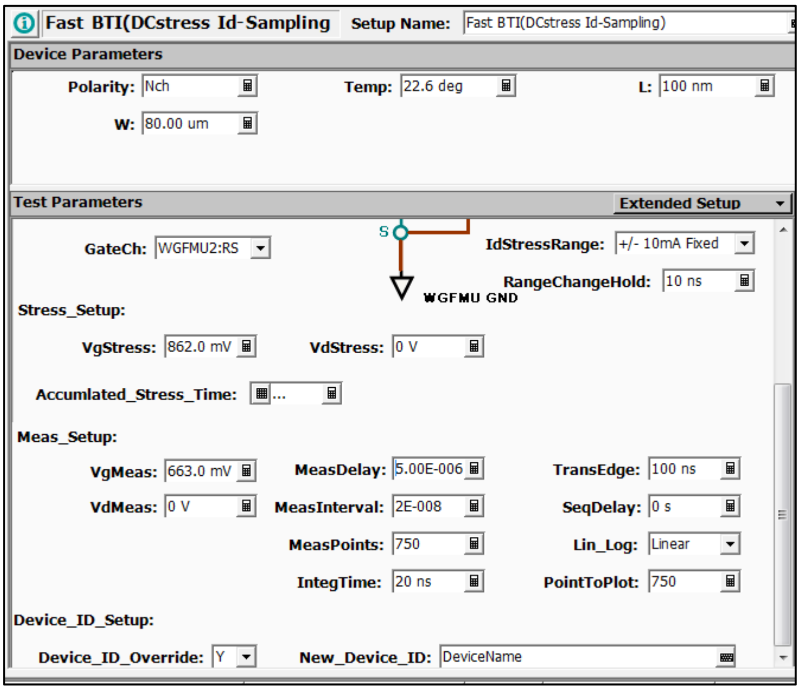
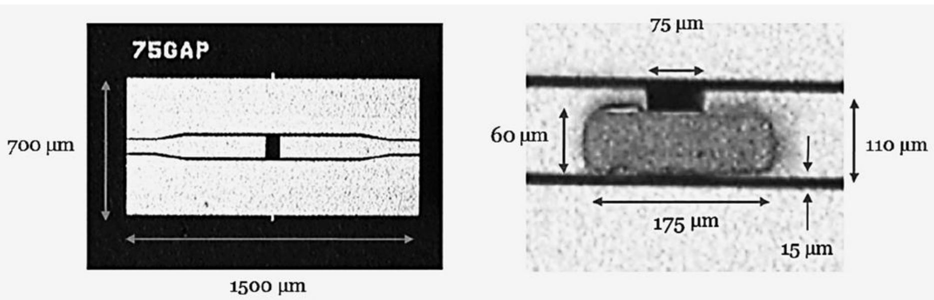


Figure 14: Example software configuration for transient response measurement of a diode.

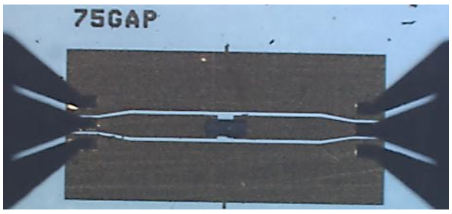
4 Schottky diode measurements

DC I-V, pulsed I-V, temperature controlled I-V, and transient current measurement procedures and results are presented in this Chapter. Discrete single anode varactor diodes from Chalmers and Tyndall have been tested. However, only measurement results from Chalmers single anode varactor diode are included in this thesis.

The diodes are soldered on coplanar waveguide (CPW) test mounts which can be contacted with ground-signal-ground (GSG) probes easily. An empty test mount, a Chalmers varactor diode soldered on the CPW and the GSG probe contact with the CPW are shown in Figure 15 (a), (b) and (c) respectively. The measurement setup is the same as in Figure 7 for all type of measurements except for temperature controlled I-V measurements (Figure 20) where the needle probes are used instead of GSG probes.



(a) (b)



(c)

Figure 15: CPW structures (a) an empty test mount (b) a Chalmers discrete diode soldered on the test mount and (c) GSG probe contact with the CPW.

4.1 DC I-V measurements

The measurement of THz Schottky diode I-V characteristics and extraction of the parameters (I-V, ideality factor, saturation current and series resistance) are performed in this section. As explained in Section 2.7, the diode parameters are extracted using two methods. In two stepped method, first η and I_s are extracted from the measured data at bias range, where the effect of series resistance is negligible. R_s is then extracted from high bias region of the I-V curve. In the next approach all three diode parameters are extracted in a single least squares error (LSE) fitting in mathematical software MATLAB.

4.1.1 Measurement setup

I-V measurement setup is the same as shown in Figure 7. Diode is mounted on the CPW and the probe contact is made. Then current measurement is carried out sweeping the voltage from 0 to 1 Volt.

4.1.2 Results

Table 2 lists the extracted parameters (with their average) from both two step and LSE fitting methods for four different diodes (two samples from each manufacturer).

Table 2: Extracted diode parameters from two different methods.

	Two-step method			**LSE fitting method**			**Average**		
Varactor diode	R_s (Ω)	η	I_{sat} (A)	R_s (Ω)	η	I_{sat} (A)	R_s (Ω)	η	I_{sat} (A)
Chalmers A6	3.1	1.18	$3.9\cdot10^{-14}$	2.9	1.21	$5.7\cdot10^{-14}$	3.0	1.19	$4.8\cdot10^{-14}$
Chalmers A10	4.5	1.16	$2.1\cdot10^{-14}$	3.6	1.21	$5.6\cdot10^{-14}$	4.1	1.18	$3.8\cdot10^{-14}$
Tyndall 4u	8.6	1.14	$3.9\cdot10^{-13}$	8.6	1.14	$9.8\cdot10^{-13}$	8.6	1.14	$6.9\cdot10^{-13}$
Tyndall 5q	7.1	1.08	$1.3\cdot10^{-13}$	6.7	1.10	$1.7\cdot10^{-13}$	6.9	1.09	$1.5\cdot10^{-13}$

Figure 16 presents an ideal I-V curve without the effect of series resistance, measured I-V curve and the fitted I-V curve for the Chalmers varactor A10 diode. From this point ahead, the results presented in this thesis are all for this sample (A10) of Chalmers single anode varactor Schottky diode.

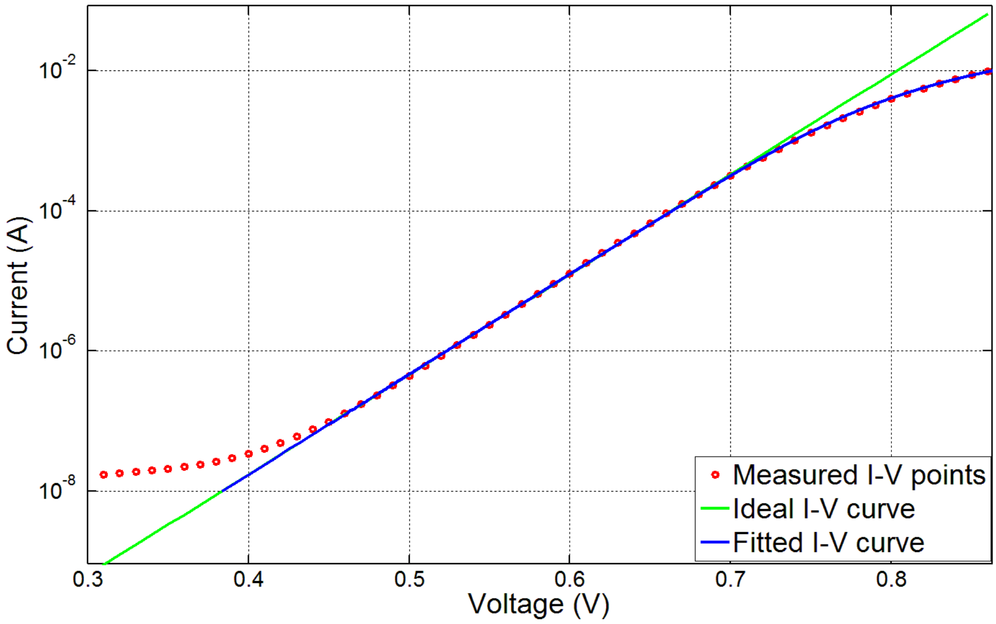


Figure 16: I-V parameter extraction using least-squares error fitting method for Chalmers single anode varactor (A10) diode.

The extraction method assumes that the temperature remains same throughout the measurement session which is not true as the diode parameters (ideality factor and saturation current) are temperature dependent (2.5) and (2.6). Hence, a new characterization method is essential to accurately extract the diode parameters.

4.2 Pulsed I-V measurement

To account the reduced thermal capability of the THz Schottky diodes, the parameter extraction should be performed in an isothermal condition which means the measurement should be performed with very fast pulses such that there is no time for the diode to react thermally. In this thesis work, suitability of the fast pulsed measurement system is studied and I-V curves for different pulse lengths are presented to differentiate with the DC I-V measurements.

4.2.1 Measurement setup and results

For a test case, pulsed I-V measurements of Chalmers single anode varactor diode are carried out using the semiconductor parameter analyzer and probe station. The effect of the pulse length in the I-V behavior of the diode is observed by applying the pulse length from 250 ns to 1 μs. Pulse period is set such that it is ten times longer than the pulse width to insure that there is no self-heating caused by the pulses.

An example timing diagram of a pulse used in this measurement is shown in Figure 17. The parameters are set for this example measurement as,

Pulse period: 10 μs; Pulse width: 1 μs; Rise and fall time: 100 ns.

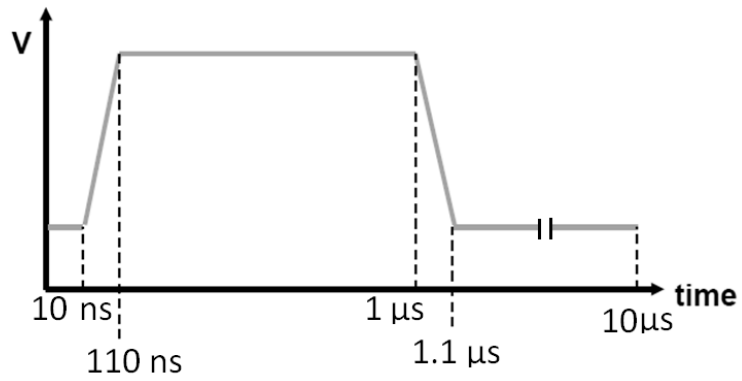


Figure 17: Example timing diagram of a single pulse used in the measurement.

Pulse shown in Figure 17 is swept from 0-1 V with the step of 10 mV and the current measurement is performed at the middle of the pulse width.

Figure 18 shows the pulsed I-V measurement curves of Chalmers A10 diode for various pulse lengths. The static DC I-Vcurve is also plotted in the same figure to observe the difference between DC and pulsed I-V measurement results. As the pulse width of the source voltage is decreased, the diode has less time to react thermally. The difference is visible clearly in the region of the I-V characteristics where the series resistance has dominant effect. For short pulses, the diode is cooler which means effect of self-heating is small and the series resistance is higher than that obtained from the DC I-V measurement. This verifies that the values of series resistance as well as other parameters obtained from the DC measurements are not accurate as they are extracted assuming constant temperature during measurement. Using pulsed I-V measurements, the extraction of the diode parameters can be performed isothermally, minimizing the self-heating effect of the diode.

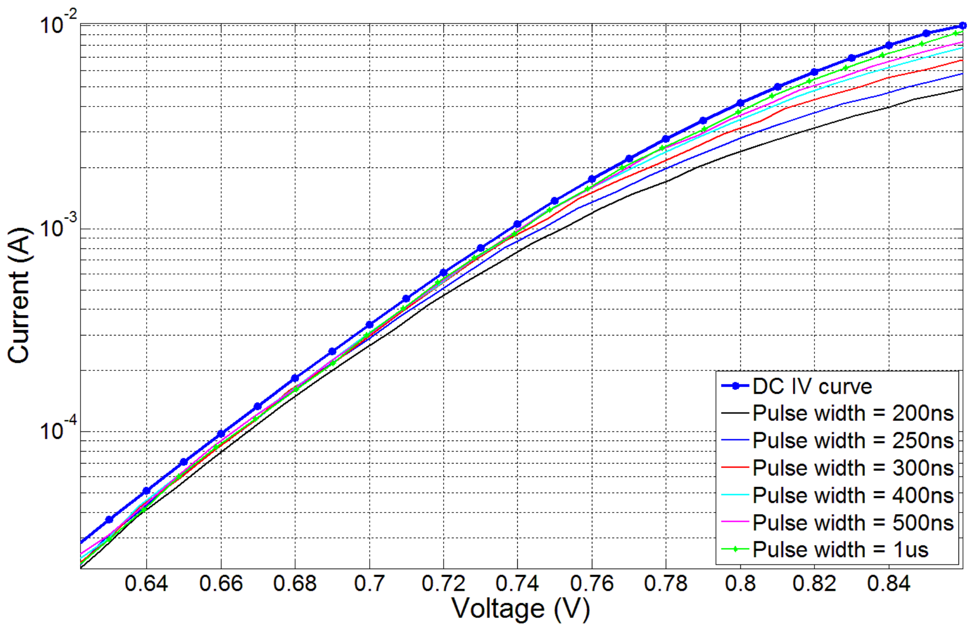


Figure 18: Pulsed I-V measurement for Chalmers varactor A10 diode using different pulse widths.

In the semiconductor parameter analyzer, an example software configuration is set as presented in Figure 19. Here the screenshot from the EasyExpert software shows the transistor in the setup, but in real measurement case two channels of the WGFMU are connected to anode and cathode terminals of the diode.

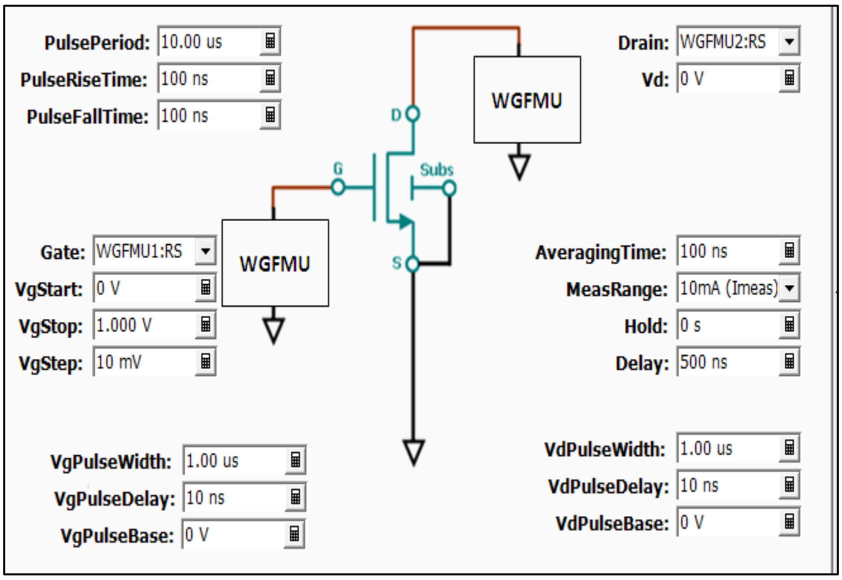


Figure 19: Parameter analyzer software configuration example for the pulsed I-V measurement.

4.3 Temperature controlled I-V measurements

The hardware setup for this measurement is shown in Figure 20, where a pair of needle probes is used instead of GSG probes as in previous setups. I-V-T measurement is carried out using a hot plate, a temperature sensor and the parameter analyzer. The temperature is adjusted from 300 K to 340 K with 5 K step and I-V measurement is carried out at each temperature points.

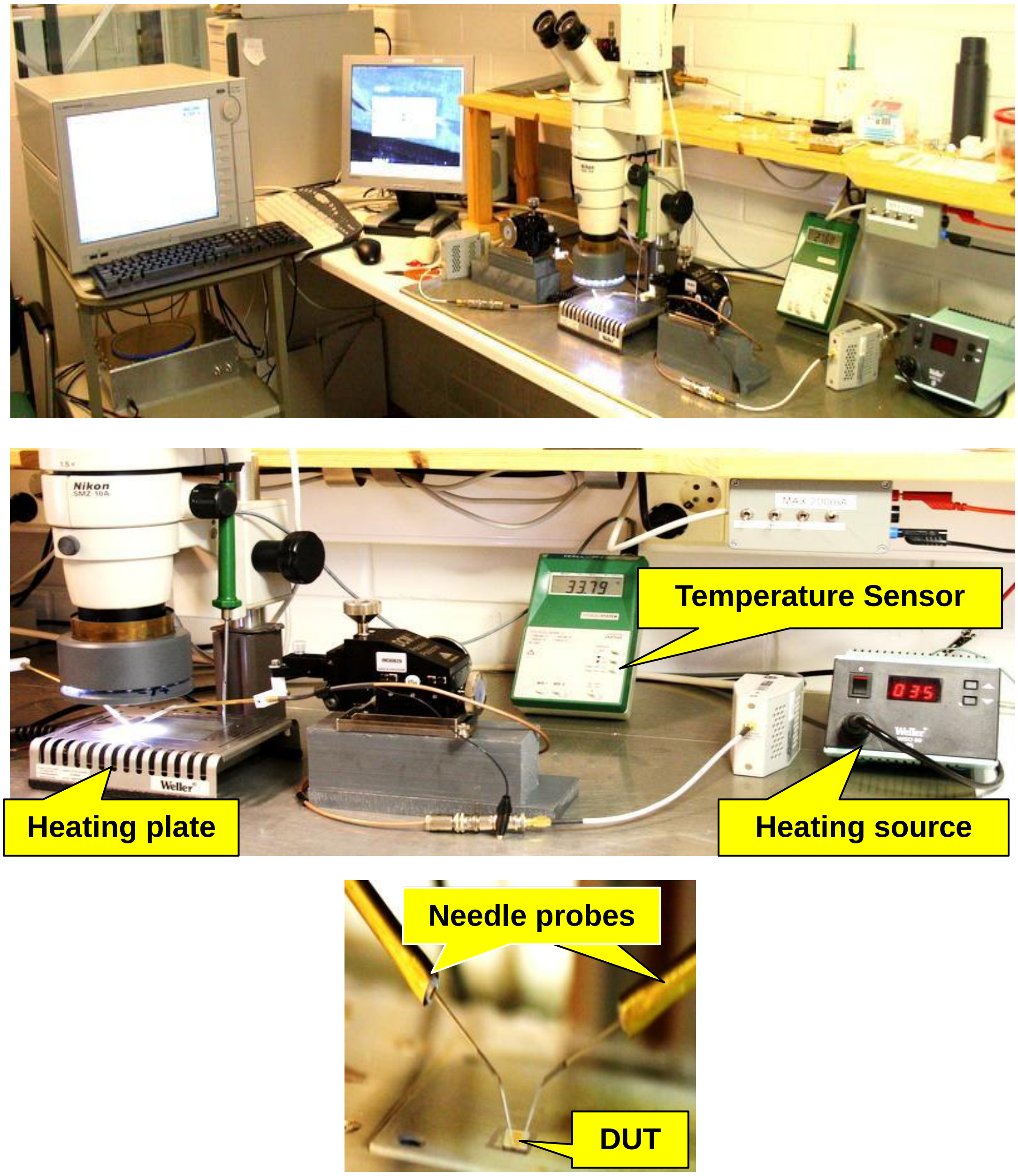


Figure 20: Temperature controlled I-V measurement setup. Needle probes are connected to two channels of the parameter analyzer. Diode is placed over a heating plate and I-V measurements are performed from 300 K to 340 K (with 5 K step). The temperature is monitored using digital thermometer attached to the heating plate.

Figure 21 shows the DC I-V characteristic curves of Chalmers A10 diode at different temperatures (300 K to 340 K). It is observed that for a constant voltage, current is higher when the temperature is increased.

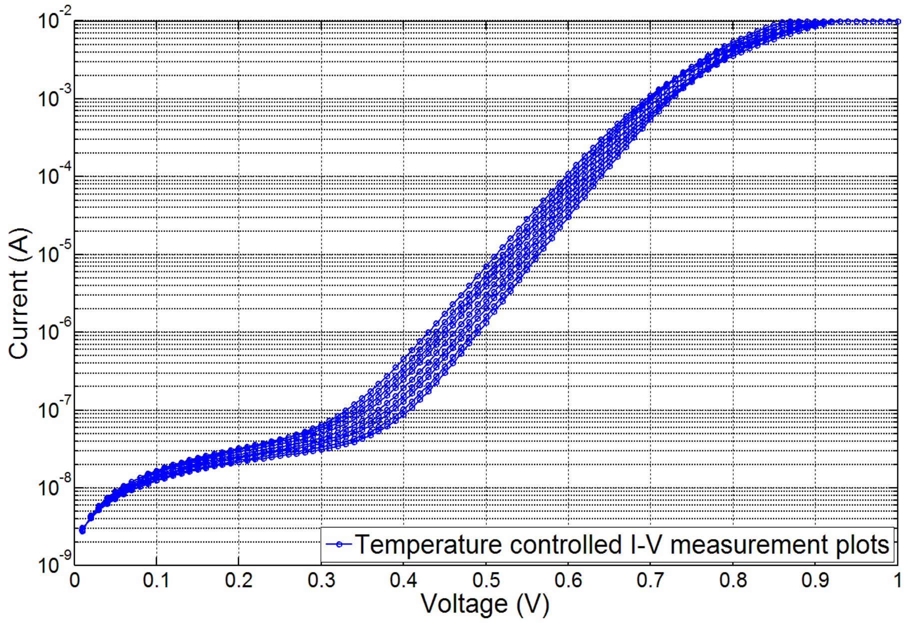


Figure 21: I-V-T characteristics curves for Chalmers A10 diode. Temperature range is from 300 K to 340 K.

4.3.1 Current-temperature calibration

To study the thermal behavior of the diode, the measured current is converted to the corresponding temperature point using the current-temperature (I-T) calibration curve as shown in Figure 22. During the calibration, there should not be any significant self-heating. To fulfill this requirement, calibration is performed at the lower current level (known as measurement current, 100 µA in this case).

First, the voltage (661 mV) corresponding to the measurement current (100 µA) is noted from the I-V curve at the room temperature. Now the current points at same voltage (661 mV) but different temperature levels are recorded from the I-V-T curves shown in Figure 21. The current versus temperature curve is then fitted in the mathematical software MATLAB. Calibration curve is to be generated for each diode under test separately.

In Figure 22, the measured points are fitted with a third degree polynomial. This fitted curve is used as the calibration curve to convert current into temperature for Chalmers A10 varactor diode.

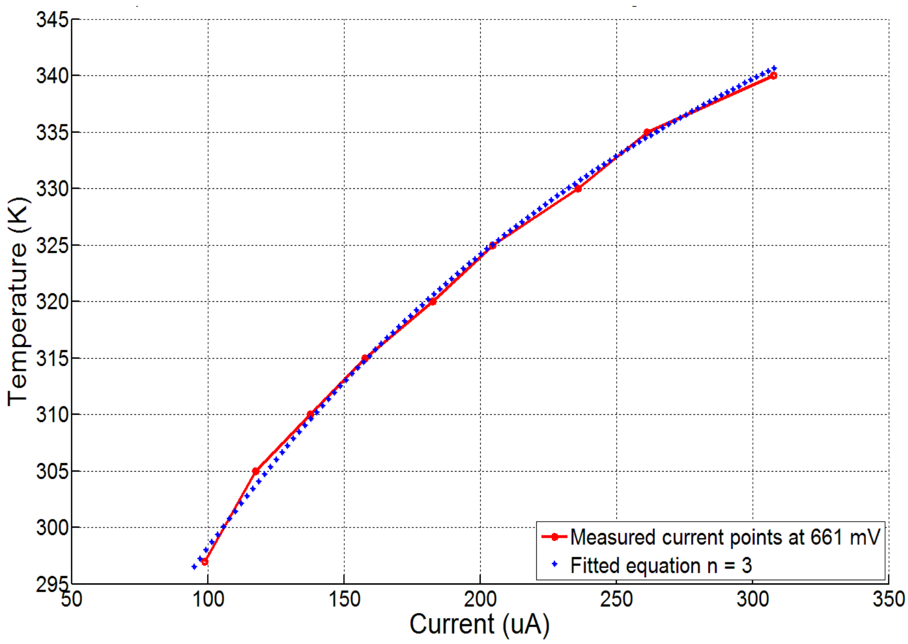


Figure 22: Temperature-current calibration curve for Chalmers A10 varactor diode. Current points are recorded from I-V-T measurement at each temperature points (at constant measurement voltage of 661 mV). Measured points are fitted with the polynomial of third degree.

4.4 Transient measurement

Earlier in the text, the DC I-V and pulsed I-V methods are presented for the electrical characterization (or parameter extraction) of the THz Schottky diodes. This section describes the measurements and results from the proposed modified MIL-STD method: transient measurement of Schottky diodes (defined in section 3.6). This method is used to extract the junction temperature of Schottky diode by measuring the transient current immediately after the termination of the heating pulse. These transient current points are converted into temperature points using current-temperature calibration which is obtained from the temperature controlled

I-V measurements. Also the thermal time-constants associated with the diode are extracted from the transient temperature response.

4.4.1 Measurement setup

Same hardware setup, as shown in Figure 7, is used for transient measurements. Only the software configurations are changed according to the type of measurement performed (DC, pulsed or transient). For transient current measurement, diode heating and current sampling setup is configured in the parameter analyzer (as in Figure 14). The heating current level is selected as 8 mA so that the diode is heated up to high temperature before the removal of the pulse and to insure no significant self-heating, the measurement current is selected as 100 μA. As mentioned earlier in the text, the voltage pulses are applied instead of the current pulses due to the limitation of the measurement system. The levels of these voltage pulses are noted from the diode I-V characteristics curve. For a test case (of Chalmers A10 diode) the heating and the measurement voltages are 840 mV and 661 mV.

4.5 Thermal time constant, thermal resistance, and junction temperature extraction

A step change in power dissipation, from heating to the measurement, provides the information on the cooling response of a semiconductor device. In this work, diode is heated for certain duration of time and an abrupt step-change in power is applied letting the diode to cool down. This cooling response of the diode from the peak junction temperature to the local ambient is measured and then fitted with an exponential function to extract the junction temperature and thermal time-constants associated to the internal heat masses of the diode.

As a test case, the cooling curve corresponding to the longest heating duration is fitted to an exponential function (4.1) which reveals the time-constants of each intermediate thermal stage as the heat flows away from the junction to the ambient.

The selection of this cooling curve (i.e. in our case, cooling curve corresponding to 10 s heating duration) is made such that the diode is heated up significantly and has reached the steady state equilibrium condition where the power applied to the diode is constant. The cooling of the diode from this steady state equilibrium condition (peak junction temperature) to the local ambient provides all the information necessary for the extraction of the junction temperature, thermal resistances (impedances) and the thermal time constants.

The thermal response of the diode after removal of the heating pulse is written as (according to [24])

$$T(t) = T_0 + T_1 \times \left(\exp\left(\frac{-t}{\tau_1}\right)\right) + T_2 \times \left(\exp\left(\frac{-t}{\tau_2}\right)\right) + \cdots + T_n \times \left(\exp\left(\frac{-t}{\tau_n}\right)\right), \qquad (4.1)$$

where T_0 is the ambient temperature (298 K). T_1, T_2,.., T_n are the temperature coefficients corresponding to the equilibrium stages. τ_1, τ_2,…, τ_n are the thermal time constants for each intermediate stage and value of ‘n’ depends on the number of time-constants used in the curve fitting.

Figure 23 shows the curve fitting (to (4.1)) example of the measured transient temperature data for 10 s heating time using one, two, three, and four time constants respectively. It is clearly visible from the plot that using one and two time constants, a good fit is not achievable which indicates the presence of more time-constants. Hence, at least three-to-four thermal time constants are present as the diode cools down to local ambient temperature.

It is observed that there are three plateaus (located around 3 μs, 50 μs and 10 ms) which indicate the presence of three well-separated time-constants in play. The thermal model is shown in Figure 24, where an idealized RC network representing the internal distribution of thermal resistances and heat capacitances of the diode is modeled.

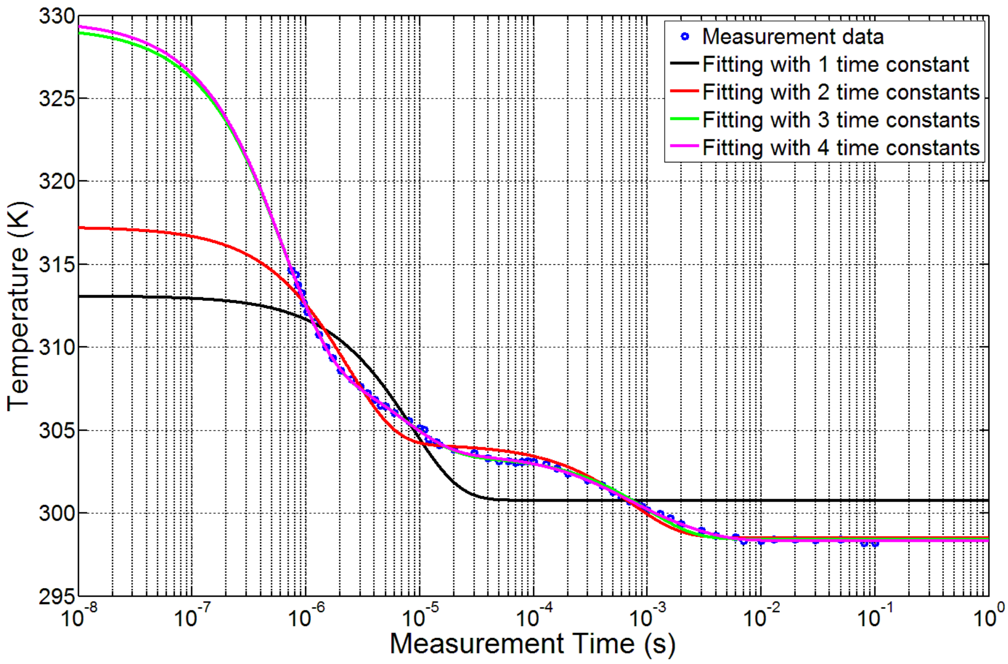


Figure 23: Thermal time constant extraction from fitting of the cooling curve.

The left most node of the network is the junction from where the heat flows out to the ambient (right most) through three intermediate thermal stages. The thermal time-constants associated to each stage are defined as the product of thermal resistance and the heat capacitance [22], [23].

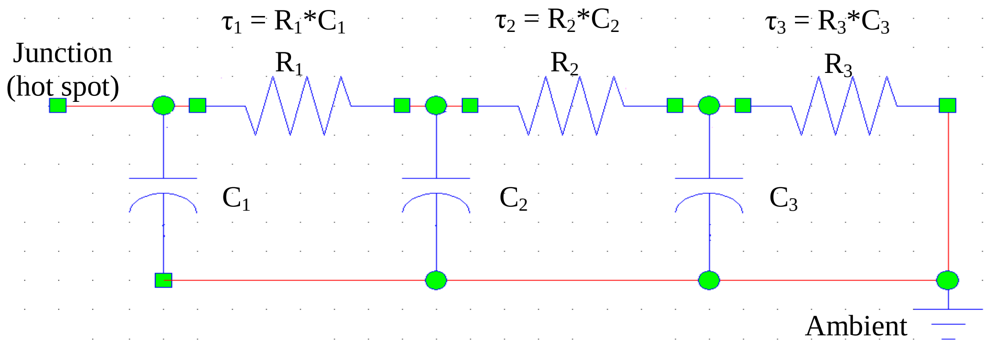


Figure 24: Circuit model of three discrete thermal resistor/capacitor pairs representing the internal distribution of thermal mass in the diode (according to [22]). Each RC combination represents an intermediate thermal stage when the heat flows from junction to the local ambient temperature.

Each plateau (in Figure 23) represents a local equilibrium condition of a thermal stage with respect to the next stage with larger time-constant (τ). The first RC stage represents the anode of the diode where the temperature change is rapid due to small heat capacitance and the last stage corresponds to the soldering of the diode to the CPW carrier that responds only when sufficient amount of heat is dissipated to vary the temperature. The intermediate stage corresponds to an internal structure of the diode between the anode and soldering. In the future work, thermal simulations are used to investigate which part of the diode could cause sufficient thermal boundary. It should be noted that if four time constants are used in the fitting, a small effect could be attributed to the thermal boundary between the CPW and thermal chuck. However, the effect of this is almost negligible.

Table 3 lists the extracted parameters from LSE curve fitting using three time-constants. The calculated thermal resistance and heat capacitances are listed in Table 4.

Table 3: Extracted parameters from curve fitting (4.1) using three time-constants.

T_0 (K)	T_1 (K)	T_2 (K)	T_3 (K)	T_{peak} (K)	τ_1 (s)	τ_2 (s)	τ_3 (s)
298.4	20.1	5.8	5.0	329.2	$6.2 \cdot 10^{-7}$	$7.8 \cdot 10^{-6}$	$9.9 \cdot 10^{-4}$

Table 4: Calculated thermal resistances and capacitances of the diode.

R_1 (K/W)	C_1 (J/K)	R_2 (K/W)	C_2 (J/K)	R_3 (K/W)	C_3 (J/K)	R_θ (K/W)
2985.1	$2.1 \cdot 10^{-10}$	855.6	$9.1 \cdot 10^{-9}$	745.5	$1.3 \cdot 10^{-6}$	4586

It is to be noted that in Figure 23, the measurement data starts from 750 ns. In Figure 25, the data starting from two additional time instants (450 ns and 1.05 μs) are also fitted. A change of ± 3 K is observed in the extrapolated peak junction temperature for ± 300 ns shift in the measurement data start time. The variation is not significant but it shows that the start point of the measurement data (in curve fitting) has some effect in the extracted peak junction temperature.

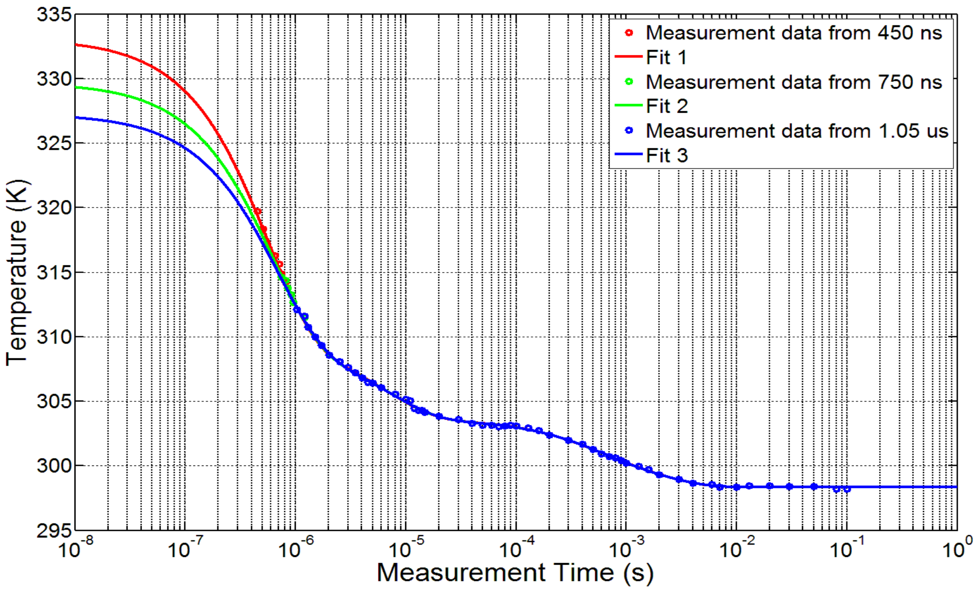


Figure 25: Curve fitting and peak junction temperature extrapolation using different start time-instants of the measured data.

5 Discussion and Conclusion

In this thesis work, the electrical and thermal characterization methods for THz Schottky diode are reviewed. For electrical characterization, DC I-V measurement methods are used to extract the diode parameters (I_{sat}, η and R_s). However, due to the reduced thermal capability (small size) of THz Schottky diodes, self-heating effect is significant. The extracted parameters are no longer accurate because of the temperature dependency of saturation current and ideality factor. Hence, a new pulsed characterization method is tested that takes into account the effect of diode self-heating.

Tests are performed to study the capability and suitability of a pulsed/transient measurement system for electrical and thermal characterization of the THz Schottky diode. Agilent B1500A Semiconductor Parameter Analyzer is used which can produce short pulses in the order of hundreds of nanoseconds and measure current in a separate channel with 2 nA current resolution. The WGFMU module in the analyzer supports the output voltage ranges of: ±3V, ±5V, -10 V to 0 V and 0 V to +10 V with output voltage resolution of 96 μV for the ± 3 V range and 160 μV for the other ranges. Five fixed current measurement ranges (from 1 μA to 10 mA) are available and the measurement resolution is 0.014% of range with the noise floor of 0.2% of range.

These features of the pulsed measurement system are suitable to perform accurate I-V and transient measurements with short pulses in the order of hundreds or nanoseconds. The same measurement setup and probe contact can be used for different measurement scenarios (DC I-V, pulsed I-V and transient current measurements) for electrical and thermal characterization of THz Schottky diodes.

Different thermal characterization methods are reviewed and their advantages and disadvantages are discussed. A new method for thermal characterization of the diode is proposed which is similar to the Military Standard method of thermal impedance testing (MIL-STD 750E 3101.4). Modifications are made to the standard method in order to suit our measurement system capability and requirements.

In the proposed new method, the thermal response of the diode to a step change in power dissipation is measured. The transient current measurements are performed immediately after the termination of the heating pulses which are then converted to the temperature points using the current-temperature relationship. Calibration is carried out using temperature controlled I-V measurements at different temperatures (300 K to 340 K with 5 K step). The heating plate has an accuracy of 2 % and the thermometer can make the reading within 3.5 % accuracy. The current values at constant voltage (measurement voltage) are recorded for each temperature points and the calibration relationship is established.

The thermal time-constants and the temperatures corresponding to the intermediate equilibrium stages (4.1) are extracted from least squares curve fitting of the cooling curve. Extraction of the peak junction temperature is carried out by extrapolating the cooling curves back to the initial state when the diode starts to cool down. It is observed that at least three thermal time-constants are associated with the diode.

The extracted first thermal time constant (corresponding to the anode) is about 0.62 μs, the second thermal time-constant is about 7.8 μs and the third, roughly 1 ms. The steady state thermal impedance, also called thermal resistance, of the diode is found to be 4586 K/W which is within the range obtained from the simulations at Chalmers (3×10^3 to 5×10^3 K/W).

In summary, the methods for electrical and thermal characterization of THz Schottky diodes have been reviewed. Limitations of the DC I-V measurements method are identified and a test is carried out to study the feasibility of a new pulsed system for diode characterization. The military standard method for thermal impedance testing has been studied and a necessary modification is proposed for the extraction of thermal time-constants, diode junction temperature, thermal resistances and heat capacitances.

5.1 Future work

The extrapolation of the peak temperature from curve fitting presents an uncertainty as we do not have transient temperature data close to zero time instant (just after removal of heating pulse). The transient current measurements are available but it is not possible to perform calibration at these high current points (due to significant self-heating) using the aforementioned DC I-V-T method.

Calibration using pulsed I-V-T measurements is to be performed in future. From this calibration, the actual temperature of the diode junction can be determined accurately.

Besides, the trapping effects in characterization and parameter extraction is also to be studied in future.

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